

# Some Implications of Neutron Mirror Neutron Oscillation

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## Abstract

We comment on a recently discussed possibility of oscillations between neutrons and degenerate mirror neutrons in the context of mirror models for particles and forces. It has been noted by Bento and Berezhiani that if these oscillations occurred at a rate of  $\tau_{NN'}^{-1} \sim \text{sec}^{-1}$ , it would help explain putative super GKZ cosmic ray events provided the temperature of the mirror radiation is  $\sim 0.3 - 0.4$  times that of familiar cosmic microwave background radiation. We discuss how such oscillation time scales can be realized in mirror models and find that the simplest nonsupersymmetric model for this idea requires the existence of a low mass (30 – 3000 GeV) color triplet scalar or vector boson. A supersymmetric model, where this constraint can be avoided is severely constrained by the requirement of maintaining a cooler mirror sector. We also find that the reheat temperature after inflation in generic models that give fast  $n - n'$  oscillation be less than about 300 GeV in order to maintain the required relative coolness of the mirror sector.

Oscillations of electrically neutral particles such as the  $K^0$  (to  $\bar{K}^0$ ),  $B_d$  (to  $\bar{B}_d$ ) mesons and the neutrinos have provided us with a wealth of information about the nature of fundamental interactions. If baryon number is not a good symmetry of nature (as is implied by grand unified theories), other oscillation phenomena can take place among electrically neutral systems e.g. neutron-anti-neutron oscillation[1] and hydrogen-anti-hydrogen oscillation[2, 3]. In the context of mirror universe models[4, 5, 6] where there is an identical copy of both the forces and matter of the standard model present side by side with the known forces and matter, a new possibility arises whereby a neutron ( $n$ ) can oscillate into its mirror partner  $n'$ . Since the mirror particles are supposed to have only gravitational or similarly suppressed interactions, the mirror neutron will not be detected by our measuring devices and the process  $n - n'$  will cause the disappearance of the neutron. Clearly, such an  $n - n'$  oscillation will have phenomenological and astrophysical implications.

Recently Berezhiani and Bento [7] have pointed out that all observations are consistent with the possibility that neutrons can oscillate to mirror neutrons on a very short time scale of about one second and that  $n - n'$  oscillations with this rate can allow some Super GZK[10] ultra high energy (UHE) cosmic rays to reach us providing that the cosmic microwave background temperature in the mirror sector is significantly lower, by say  $x = T'/T \sim 1/3$  than in our visible sector. The paper[7] correctly pointed out that :

i) the strict bounds[8] on  $n \longrightarrow 3\nu$  utilizing the resultant nuclear excitation and gamma emission do not apply here as  $n \rightarrow n'$  oscillations inside nuclei is forbidden by energy conservation;

ii) the Grenoble bounds [9] on the neutron -anti-neutron oscillation rate  $\tau_{n-\bar{n}}^{-1} < 10^{-8} \text{sec}^{-1}$  coming from the absence of dramatic anti-neutron annihilation events also does not apply to  $n \rightarrow n'$  oscillation .

An  $n - n'$  oscillation rate as large as  $1 \text{sec}^{-1}$  would of course imply a reduction of the reactor neutron flux by as much as 1%. In view of other neutron loss mechanisms at this level which can amount to as much as 5% or more,  $1 \text{sec}^{-1}$ . can be used as a crude upper bound on the rate and is presumably not inconsistent with observations.

Coming to galactic propagation of neutrons, first point to note is that since the Lorentz enhancement of the magnetic field compensates for time dilation, in order to have unquenched  $n \rightarrow n'$  oscillations that would allow super GKZ cosmic rays (CR) [10] on Earth, requires that along most of the  $\sim (100)$  Mega parsec distance travelled by the neutron, the B field

must be smaller than  $10^{-15}$  Gauss. While this seems like a severe demand, the authors of [7] argue that it is conceivably achieved in large extragalactic patches .

Our purpose in this brief note is to discuss some theoretical implications of having a relatively “fast”  $n - n'$  oscillation in the context of simple mirror models. We also note some new phenomenological and cosmological consequences of this possibility.

We consider two classes of mirror models: one without supersymmetry and the other with supersymmetry. We point out that in the context of non-supersymmetric models, simplest realizations of “fast”  $n - n'$  oscillations together with a nonvanishing neutrino mass would require the existence of light ( $\sim 30 - 3000$  GeV) color triplet boson. This could provide an interesting test of the model. In the presence of supersymmetry, a new class of models can be constructed where the ordinary and mirror bino’s  $\tilde{B}$  and  $\tilde{B}'$  mix to give  $n - n'$  transition. These models lead to new phenomena such as  $K^0 - \bar{K}^0$  as well as Higgs-mirror-Higgs mixing with interesting implications. In this case, there exist severe constraints on the supersymmetry breaking parameters of the model.

We also point out that such “fast”  $n - n'$  oscillation times would require that the reheat temperature after inflation has to be lower than about 100 GeV in order to maintain the required relative “coolness” of the mirror sector in such models. Such low reheat temperatures would necessitate the existence of new mechanisms for the origin of matter.

We also make a phenomenological remark that fast  $n - n'$  transitions lead to the interesting possibility of having neutrons effectively ”tunnel” through large amount of material. This for instance could lead to an upward flux of neutrons from the Earth during solar flares.

## I. MODELS FOR “FAST” $n - n'$ OSCILLATION AND IMPLICATIONS

In this section, we consider minimal theoretical schemes which can lead to “fast”  $n - n'$  oscillations and study their consequences. We will consider the minimally replicated standard model gauge group i.e.  $[SU(3)_c \times SU(2)_L \times U(1)_Y] \times [SU(3)'_c \times SU(2)'_L \times U(1)'_Y]$  where the unprimed group operates in the visible sector and the primed group operates in the mirror sector. The two sectors communicate only via gravity as well as via very weakly interacting particles. If the only communications between the two sectors were via gravity, the effective  $n - n'$  operator  $u^c d^c d^c u'^c d'^c d'^c$  would have a strength of  $1/M_{Pl}^5$  and would lead to oscillation times which are minuscule and of no consequence. We therefore

need other interactions between the two sectors in a way that respects gauge invariance and renormalizability in order to get sizable  $\tau_{nn'}$ . We outline two such models below. Both the models will build on the basic particle content of the mirror model given below (for the nonsupersymmetric case):

particles	visible sector	mirror sector
Gauge bosons	$W, Z, \gamma$	$W', Z', \gamma'$
Matter	$Q \equiv (u, d)$ $u^c, d^c, e^c, \nu^c$	$Q' \equiv (u', d')$ $u^{c'}, d^{c'}, e^{c'}, \nu^{c'}$
Higgs fields	$H$	$H'$

Clearly in the above table, the fields  $\nu^c$  and  $\nu'^c$  are singlets under both the gauge groups and mirror partners of each other. If they are electroweak singlets, they could couple to particles in either sector[11]. A simpler version of the theory where the sectors communicate only via the term mixing the  $\nu^c$  with  $\nu'^c$  can be obtained if there is an extra  $U(1)$  in both sectors, such that both  $\nu^c$  and  $\nu'^c$  are nonsinglets under this and there is a connector field  $\phi$  with quantum numbers such that we have the coupling  $\nu^c \nu'^c \phi$  allowed. The vev of the  $\phi$  field would then connect the two sectors. In any case we will assume that the interaction Lagrangian for the model to consist of two terms:  $\mathcal{L} = \mathcal{L}_Y + \mathcal{L}'$  where  $\mathcal{L}_Y$  in each sector will have the standard form with usual Yukawa couplings as follows:

$$\begin{aligned} \mathcal{L}_Y = & h_u Q H u^c + h_d Q d^c \tilde{H} + h_\ell L e^c \tilde{H} + h_\nu L \nu^c H \\ & +(Q \rightarrow Q', L \rightarrow L' \cdots etc) \end{aligned} \quad (1)$$

The gauge couplings and the above Yukawa couplings do not lead to  $n - n'$  oscillation and we need to add an effective dimension 6 operator in each sector plus a connecting term:

$$\begin{aligned} \mathcal{L}' = & \frac{1}{M^2} (\nu^c u^c d^c d^c + \nu'^c u'^c d'^c d'^c) \\ & + \delta M \nu^c \nu'^c + h.c. \end{aligned} \quad (2)$$

Given these interactions, having sizable  $n - n'$  transition and also nonvanishing neutrino masses puts constraints on the parameters  $M$  and  $\delta M$  of the model. In the case at hand we have  $(B - L - B' + L')$  conserved.

In this model, the neutrino is a Dirac fermion due to  $(B - L - B + L')$  conservation, with a mass in the range of 0.1 eV connecting the  $\nu$  and  $\nu'$ . This is given by the usual seesaw

diagram except that instead of a Majorana mass for the right handed neutrino, we have the  $\delta M$  interaction. This gives

$$m_\nu \simeq \frac{(h_\nu v_{wk})^2}{\delta M} \quad (3)$$

This implies that  $h_\nu^2 \frac{1}{\delta M} \simeq 10^{-14} \text{ GeV}^{-1}$ .

The six quark operator leading to  $n - n'$  oscillation has the strength:

$$G_{6q} \simeq \frac{1}{M^4 \delta M} \simeq \frac{10^{-14} \text{ GeV}}{h_\nu^2 M^4} \quad (4)$$

$G_{6q}$  is related to the  $n - n'$  transition operator roughly by the formula  $G_{n-n'} \sim \Lambda_{QCD}^6 G_{6q} \sim 10^{-4} G_{6q}$  [12] (all in GeV units). Putting all this together and requiring that  $\tau_{n-n'} \simeq 1 \text{ sec}$ . implies that  $\sqrt{h_\nu} M \simeq 30 \text{ GeV}$ . For  $h_\nu \simeq 1 - 10^{-4}$ , we must have  $M \simeq 30 - 3000 \text{ GeV}$ .

To see the meaning of this scale  $M$ , we can imagine a higher scale theory, where there is a particle connecting the two quarks and the  $\nu^c q$  whose exchange would lead to the interaction  $u^c d^c d^c \nu^c$ . This particle would be a color triplet and must have mass  $M \sim 30 - 3000 \text{ GeV}$  in order to have required “fast”  $n - n'$  oscillation. It must couple only to the  $u^c d^d$  and  $d^c \nu^c$  and not to any other fermion of the standard model to be consistent. For example if it coupled to  $u^c e^c$  it would lead to extremely fast proton decay and will therefore be ruled out. The existence of such a low mass particle could be searched for in colliders and thereby provide a test of the possibility of “fast”  $n - n'$  oscillation.

This particle will decay to two jets and will imitate the squark in an R-parity violating supersymmetric theory. Present experiments would eliminate any such particle below a 100 GeV. <sup>1</sup>

Since the neutrino is a Dirac fermion, observation of neutrinoless double beta decay will rule out this model. It will not lead to any oscillation between active and sterile neutrinos and as such cannot accommodate the LSND results. Therefore if MiniBooNe confirms the LSND results, this model will be ruled out. Furthermore, there is no neutron-anti-neutron oscillation in this case.

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<sup>1</sup> A simple way to avoid having such a low mass color triplet field would be to have two standard model singlet fermions, one responsible for neutrino mass and another for  $n - n'$  oscillation. But in such a case, one will have to add extra symmetries to explain why they do not couple to each other.

## II. MAJORANA NEUTRINO AS A WAY TO ACCOMMODATE LSND

The model above can be modified to incorporate a Majorana neutrino as well as the LSND results as follows. If the  $(B - L - B' + L')$  symmetry responsible for neutrino being a Dirac fermion can be broken by adding a mass term  $M_N \nu^c \nu^c$ , this model leads to Majorana neutrinos in each sector. Furthermore, if we assume that mass parameters  $M_N$  are different from those in the mirror sector, one could make the mirror neutrino masses to be larger (say  $\sim 1$  eV) thereby making it possible to accommodate the LSND results in the usual manner[13]. In such a version, the high scale sector is mirror asymmetric which would go more naturally with asymmetric inflation whereas the TeV scale low energy sector is fully mirror symmetric, so that  $n$  and  $n'$  have the same mass. Let us discuss what constraints are imposed on this model by a “fast”  $n - n'$  oscillation.

A new feature of this model compared to the previous model is that it will lead to oscillations between  $n$  and  $\bar{n}$  with a strength  $\simeq \frac{M_N}{M^4(\delta M)^2}$  which gives

$$\tau_{n-\bar{n}} \simeq \tau_{n-n'} \frac{\delta M}{M_N} \quad (5)$$

To be consistent with the present lower limit on  $\tau_{n-\bar{n}} \leq 10^8$  sec.[9] with  $\tau_{n-n'} \sim 1$  sec., we must have  $M_N \leq 10^{-8} \delta M$  making the  $\nu^c$  and  $\nu^c$  a pseudo-Dirac pair. This is a very high degree of fine tuning of parameters. One could interpret this as follows: (a) if the  $n - n'$  oscillation time scale is as fast as second and (b) if the mirror neutrinos are responsible for explaining the LSND results and/or the neutrinos are established to be Majorana fermions, then  $n - \bar{n}$  oscillation time should not be very much higher than its present lower limit of  $10^8$  seconds without making the level of fine tuning much worse. A search for  $n - \bar{n}$  would then provide a test of this model.

## III. A SUPERSYMMETRIC MODEL

The constraint of a low mass color triplet scalar particle can be avoided if we consider the following supersymmetric model. Another way to look at it is to ask if the low mass scalar triplet of the previous sections could be a superpartner. This assumption has other constraints that we discuss below.

This model is based on the same particle content as in Table I except for the fact that each field in the table is to be understood as a superfield that contains a fermion as well as a

boson in it and there will be two Higgs fields  $H_{u,d}$  as required in MSSM. The neutrino masses in this model could arise from the existence of the  $\nu^c$  field as in the nonsupersymmetric case and become a Dirac fermion or they could alternatively arise from the R-parity violating terms in each sector. The  $n - n'$  oscillation in this case arises from the presence of bino-mirror-bino mixing (bino being the superpartner of the  $U(1)_Y$  gauge field of the standard model) so that the neutrino mass and the  $n - n'$  oscillation are decoupled from each other leading to very different character for this model.

The superpotential of this model is given by

$$\begin{aligned}
W = & h_u Q H_u u^c + h_d Q d^c H_d + h_\ell L e^c H_d + h_\nu L \nu^c H_u + \\
& \lambda_q u^c d^c d^c \\
& +(Q \rightarrow Q', L \rightarrow L' \dots etc)
\end{aligned} \tag{6}$$

The communication between the visible and the mirror sector is done via the bino mixing term  $M_{BB'} \tilde{B} \tilde{B}'$  as already mentioned. This term is gauge invariant but breaks supersymmetry softly and is allowed. A typical Feynman diagram giving rise to  $n - n'$  oscillation is shown in Fig. 1 and has the strength

$$G_{6q} \simeq \frac{\lambda_q^2 M_{BB'}}{M_{\tilde{q}}^4 M_B^2} \tag{7}$$

For  $M_{BB'} \leq M_B \simeq 100$  GeV, and  $M_{\tilde{q}} \simeq$  TeV, we get the constraint  $\lambda_q^2 M_{BB'} \simeq 10^{-2}$  GeV.

In this case there is another constraint coming from the fact that a gluino mediated graph can lead to  $N - \bar{N}$  oscillation and present bounds on this process imply that

$$\tau_{n-n'} \simeq \frac{M_B^2}{M_{BB'} M_{\tilde{G}}} \tau_{n-\bar{n}}. \tag{8}$$

This implies that for  $\tau_{nn'} \sim 1$  sec., the gluino has to be superheavy ( $M_{\tilde{G}} \sim 10^{10}$  GeV for  $M_{BB'} \sim M_B \sim 100$  GeV.) This represents a severe degree of fine tuning and is certainly different from the conventional supersymmetry scenarios.

If we accepted this scenario, there are cosmological implications which put further constraints. This has to do with a class of new effects in the model that lead to mixing between normal and mirror Higgs fields via radiatively induced interactions of type  $\lambda_H (H_u H_d H'_u H'_d)$ . They arise at the one loop level via diagrams of type in Fig.2. This effect can be estimated to be  $\lambda_{eff} \simeq \frac{g_1^4 M_{BB'}^2 \mu^2}{16\pi^2 M_{\tilde{S}}^4} \simeq 10^{-4}$  in the simplest assumption of  $M_{BB'} \simeq \mu \simeq M_S \sim$  TeV. Note

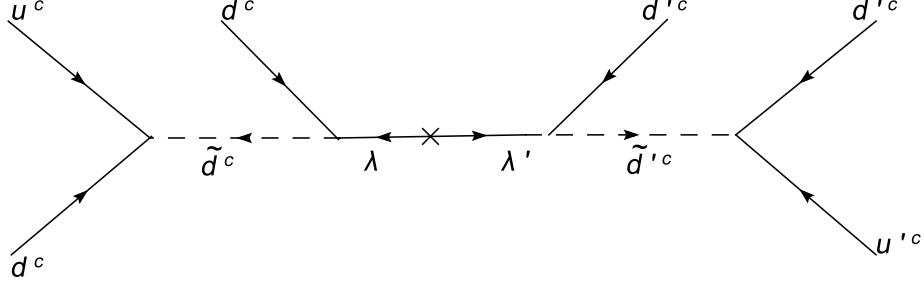


FIG. 1: The supersymmetric diagram for neutron mirror-neutron oscillation caused by  $\tilde{B} - \tilde{B}'$  mixing.

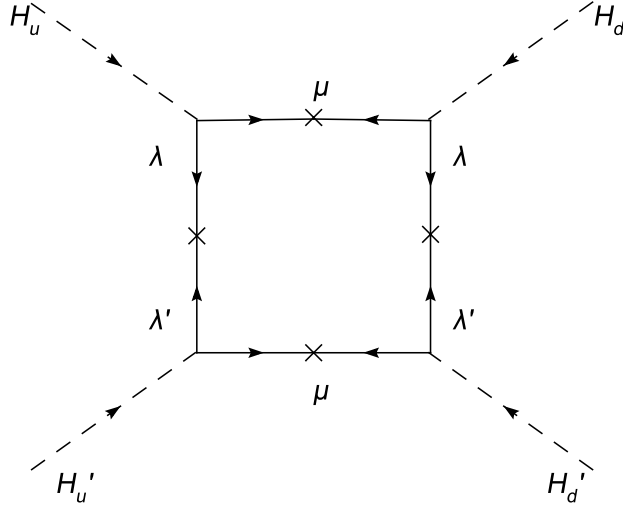


FIG. 2: Higgs mirror-Higgs mixing induced by  $\tilde{B} - \tilde{B}'$  mixing.

that this estimate is independent of the gluino mass. The value of  $\lambda_{eff}$  will have implications for cosmology and maintaining the temperature asymmetry between the two sector[14] that we discuss below.

#### IV. COSMOLOGY OF FAST $n - n'$ OSCILLATION

We saw from the above discussion that a transition time  $\tau_{n-n'} \simeq 1$  sec. corresponds to a strength of the six quark operator of order of  $10^{-20} \text{ GeV}^{-5}$ . This has to be consistent with another requirement of the mirror models that the asymmetry in the temperatures must be maintained down to the BBN epoch. To ensure this, we must have the process  $u^c d^c d^c \rightarrow u'^c d'^c d'^c$  induced by the  $n - n'$  operator must be out of equilibrium all the way



down to the same epoch. To see what constraint it imposes on the model, we note that the out of equilibrium condition is given by:

$$10^{-40}T^{11} \leq \sqrt{g^*} \frac{T^2}{M_{Pl}} \quad (9)$$

This implies that above a temperature of  $T_* \simeq 300$  GeV, the  $n - n'$  interaction will bring the visible and the mirror sectors into equilibrium, which is undesirable from the point of view of BBN. This means that the reheat temperature of the universe after inflation must be less than 300 GeV. This of course puts other constraints on the model e.g. how to generate baryon asymmetry etc.

In the particular case of the supersymmetric model, the induced  $H^2 H'^2$  can also lead to transitions between the visible and the mirror sector. The strength of this transition is  $\sim 10^{-8}T$ . Comparing this with the Hubble expansion rate, the out of equilibrium condition gives that for the first case  $T \leq T_* \simeq 10^9$  GeV, the two sectors are in equilibrium. Clearly this is in contradiction with the same constraint from  $n - n'$  transition.

This would imply that the supersymmetric model for fast  $n - n'$  transition given above is incompatible with cosmology unless further fine tuning of parameters is imposed ( such as vanishing  $\mu$  terms for instance).

## V. PHENOMENOLOGICAL IMPLICATIONS

We now turn to discuss some phenomenological implications of having a “fast”  $n - n'$  oscillation.

First we consider the propagation of reactor neutrons. Clearly the deficiency here is the “short length” over which the Grenoble neutrons propagate which for these hypothermal neutrons amounts to a 1sec time interval. This is so since one needs to strongly shield the earths magnetic field so as not to quench to much even slow oscillations like the above  $n \rightarrow \bar{n}$  oscillations with oscillation time of  $10^8 sec$ . However much faster (say  $sec^{-1}$ )  $n \rightarrow n'$  oscillation rates of the type considered here could survive much larger -say  $B = 10^{-3}$  Gauss fields.

Far longer propagation of order the neutron 15 minutes lifetime are experienced by neutrons detected during solar flare. Travelling with mildly relativistic speeds the  $\sim 150$  million Km distance from sun spots to earth they could readily oscillate into  $n'$ s in the intervening

space which have  $B < 10^{-3}$  Gauss. This yields a factor two reduction in the neutron flux which however cannot be ascertained unless we have an accurate knowledge of the neutron flux at the source.

Note however that a satellite located at a few earth radii distance would detect some flux of up going neutrons even when the solar flare occurs at the opposite hemisphere and is completely eclipsed by the earth . The point is that all the  $n$ 's making up 50% of the initial flux penetrate through the earth and then -just like in [7] super-GKZ scenario some fraction therefore will oscillate back into neutrons. Clearly to optimize the  $n' \rightarrow n$  oscillations the satellite should be located as far as possible ,increasing travel time and minimizing the B fields . Unfortunately for distances  $l \gg R_{Earth}$  the solid angle and the frequency and duration of the eclipsed Solar flares will be minimal . Consider however a generic satellite which is just one earth radius where the magnetic field ( falling like  $(R/R_{earth})^{-3}$  ) is  $\sim 0.1$  Gauss. Along the way to it  $\sim 10^{-4}$  of the  $n$ 's will have reconverted back into ordinary neutrons- and during total eclipse even such a weak signal delayed by just  $\sim 3R_{Earth}/c \sim 0.06$  sec may be detectable. In this short note we have not attempted to see if there are indeed enough relevant data of this type , or in connection with reactor,pulsed intense neutron beams which could potentially impact on the [7] suggestion <sup>2</sup>.

## VI. SUMMARY AND CONCLUSION

In this brief note we have explored to what extent neutron-mirror neutron oscillation, a phenomenon which is in principle possible in the mirror models, can be realized in the context of realistic models. We find that while a “fast”  $n - n'$  oscillation can be realized in a nonsupersymmetric model, it imposes a nontrivial constraint on the model of having a 10-1000 GeV color triplet scalar boson in the visible sector which could be detected at the LHC. We also note that if  $n - n'$  oscillation time is as fast as one second and LSND result is explained by mirror neutrinos, then  $n - \bar{n}$  oscillation should be observable unless the parameters of the model are severely fine tuned. We also show that cosmology of these

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<sup>2</sup> It is amusing to note parenthetically that the fact that  $|n\rangle + |n'\rangle$  and  $|n\rangle - |n'\rangle$  are the propagating states does not ( Like in the  $K\bar{K} - K_L K_S$  system ) prolong the life time of the antisymmetric combination . The reason being that the  $n$  and the  $n'$  -unlike the kaon and anti-kaon- decay into different final states ( $p e \nu - p' e' \nu'$ ) and the decay amplitudes cannot ( negatively) interfere.

models require that the reheat temperature after inflation in these models must be less than 300 GeV.

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